

Astronomy Applications of Adaptive Optics at Lawrence Livermore National Laboratory

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Astronomy applications of Adaptive Optics at Lawrence Livermore National Laboratory

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ABSTRACT

Astronomical applications of adaptive optics at Lawrence Livermore National Laboratory (LLNL) has a history that extends from 1984. The program started with the Lick Observatory Adaptive Optics system and has progressed through the years to lever-larger telescopes: Keck, and now the proposed CELT (California Extremely Large Telescope) 30m telescope. LLNL AO continues to be at the forefront of AO development and science.

INTRODUCTION

This paper details the contributions made by LLNL to several astronomy AO projects. The projects discussed here, the Lick Adaptive Optics System, the Keck Adaptive Optics system, and AO for Extremely Large Telescopes (ELT's), represent a partial list of LLNL's efforts in the field.

HISTORY

Adaptive optics has a long history at Lawrence Livermore National Laboratory, beginning in the 1980's with the Strategic Defense Initiative (SDI). SDI required deformable mirrors in order to correct atmospheric turbulence for a high-power laser weapon against objects in low-earth trajectory¹. At about the same time, interest was developing a sodium guide star for measuring the atmospheric aberrations.

In parallel, the AVLIS (Atomic Vapor Laser Isotope Separation) program was developing the tunable dye laser to be used in a uranium-enrichment process; this work began in 1970². The dye laser would later be developed for use in creating a sodium guide star, initially for SDI. In 1984, LLNL physicist Claire Max was one of a team of DOD consultants that conceived of using a laser fluorescence of the earth's sodium mesosphere as a beacon for atmospheric turbulence sensing.

LICK OBSERVATORY ADAPTIVE OPTICS SYSTEM

1. History

The close ties between the University of California (UC) and LLNL, along with the proximity to LLNL of the UC-operated Lick Observatory (located in the mountains east of San Jose), gave a natural direction for the LLNL astronomical AO project. The following describes the timeline of the Lick AO system:

1984: First proposals for using sodium guide stars for adaptive optics.

1991: Sodium guide stars declassified. LGS experiment proposed at LLNL^{3,4}

1993: Experiment with sodium laser guide star using 1000W AVLIS laser and 0.5m telescope at LLNL^{5,6}; Hartmann sensor tested

1993: Prototype fitted to 40-inch Nickel telescope at Lick Observatory⁷

1994: First image improvement using natural guide stars on 3 meter telescope at Lick Observatory⁸

1995: Initial commissioning of dye laser at Lick Observatory⁹

1996: First image improvement using sodium laser guide stars at Lick Observatory¹⁰

1999: Engineering of facility-grade Lick AO instrument begins

1999: Delivery of IRCAL, a science camera designed for the Lick AO system¹¹
 1999: Dramatic improvement of AO system performance using NGS and LGS¹²; instrument opened to astronomers
 2001: Day-to-day operations of AO bench transferred to Lick Observatory personnel
 2002: Day-to-day operations of dye laser transferred to Lick Observatory personnel

Currently, day-to-day operations are performed by Lick personnel. In a typical LGS observing scenario, one person runs the AO system (acquiring guide stars, closing the loop, taking telemetry data), and one person operates the laser. One person, typically the observer, also runs the science camera (IRCAL). Well-trained individuals can run the science camera and AO system simultaneously.

The individual running the AO system is often a resident support scientist, although observers can be trained on the instrument, especially if they have learned the fundamentals of AO and AO observing. All daily maintenance and alignment responsibilities are carried out by the resident support scientists, primarily Dr. Elinor Gates. The AO system is mounted on the cassegrain focus of the telescope; after this, the system is aligned in the afternoon. A nightly "tuning-up" of the system calibration then follows.

The laser is maintained by one of the observatory technicians. He also operates the laser on observing nights from the observers' control room. Most of the laser equipment is either in a laboratory below the dome floor or on the telescope, but this location facilitates communication among the AO operator, the observer, and himself.

2. System description

The Lick laser guide star/adaptive optics system is installed at the f/17 cassegrain focus of the 3m Shane Telescope. Most of the major components of the system are as given in reference 13 and are summarized in the following table:

Deformable mirror	LLNL-built, 127 actuators, 61 actuators controlled, triangular pattern, electrorestrictive (PMN) actuators
T/t mirror	3" mirror mounted on Physik Instrumente 2-axis tilt platform, 1200Hz bandwidth
Fast wavefront sensor	Shack-Hartmann wavefront sensor, 40 subapertures (44cm diameter on primary), Adaptive Optics Associates camera with Lincoln Lab 64x64 CCD, read noise 7e ⁻ per pixel at 1200 frames/sec; 4x4 center-of-mass or quad-cell centroiding algorithm
Tip-tilt sensor	Quad-cell photon-counting avalanche photodiode with ± 2 arcsec FOV, pupil imaged onto the fibers feeding APD's
Wavefront control computer	160Mflop Mercury VME with 4 Intel i860 processors, operated at up to 500Hz sample rate, with 0db crossover up to 30Hz.
Laser guide star	Sodium beacon--tunable dye laser, pumped by flash-lamp-pumped frequency doubled Nd:YAG lasers, launched by 30cm aperture refractive telescope, 18 W average power with 100ns pulse width and 11kHz repetition rate.
Infrared camera	PICNIC HgCdTe 256x256 CCD, 30e ⁻ read noise, .02e ⁻ per second dark current, 1.15x relay optics, 0.076 arcsec/pixel, 800-2550nm, 77K, QE>60%, speckle/subarray/coronagraph modes, 14 filters+blank+open (including grisms) ; this upgrades the previous LIRC-II camera.
Visible scoring camera	Photometrics CH250 (1035x1317, 6.8 μ pixels, Kodak 0400 detector, thermoelectrically cooled)
Slow wavefront sensor	Similar to fast wavefront sensor, but using Photometrics CH250 CCD described above

3. Performance

The first question in judging astronomical adaptive optics systems is “What is your Strehl ratio and with what brightness guide star?” The following plots summarize Strehl performance versus NGS brightness and seeing, and also minimum requirements for guide star brightness¹⁴. In general, a $V \approx 13.5$ guide star within ≈ 1 arcmin of the science target is necessary for NGS operation. A $V \approx 17$ guide star within ≈ 1 arcmin of the science target is necessary for LGS operation (this star functions as a tip/tilt guide star). The sky coverages corresponding to these two cases (NGS & LGS) are $<1\%$ and $>50\%$ respectively. Bright guide star Strehl ratios are about 0.8 at 2.2μ in somewhat better-than-average seeing conditions.

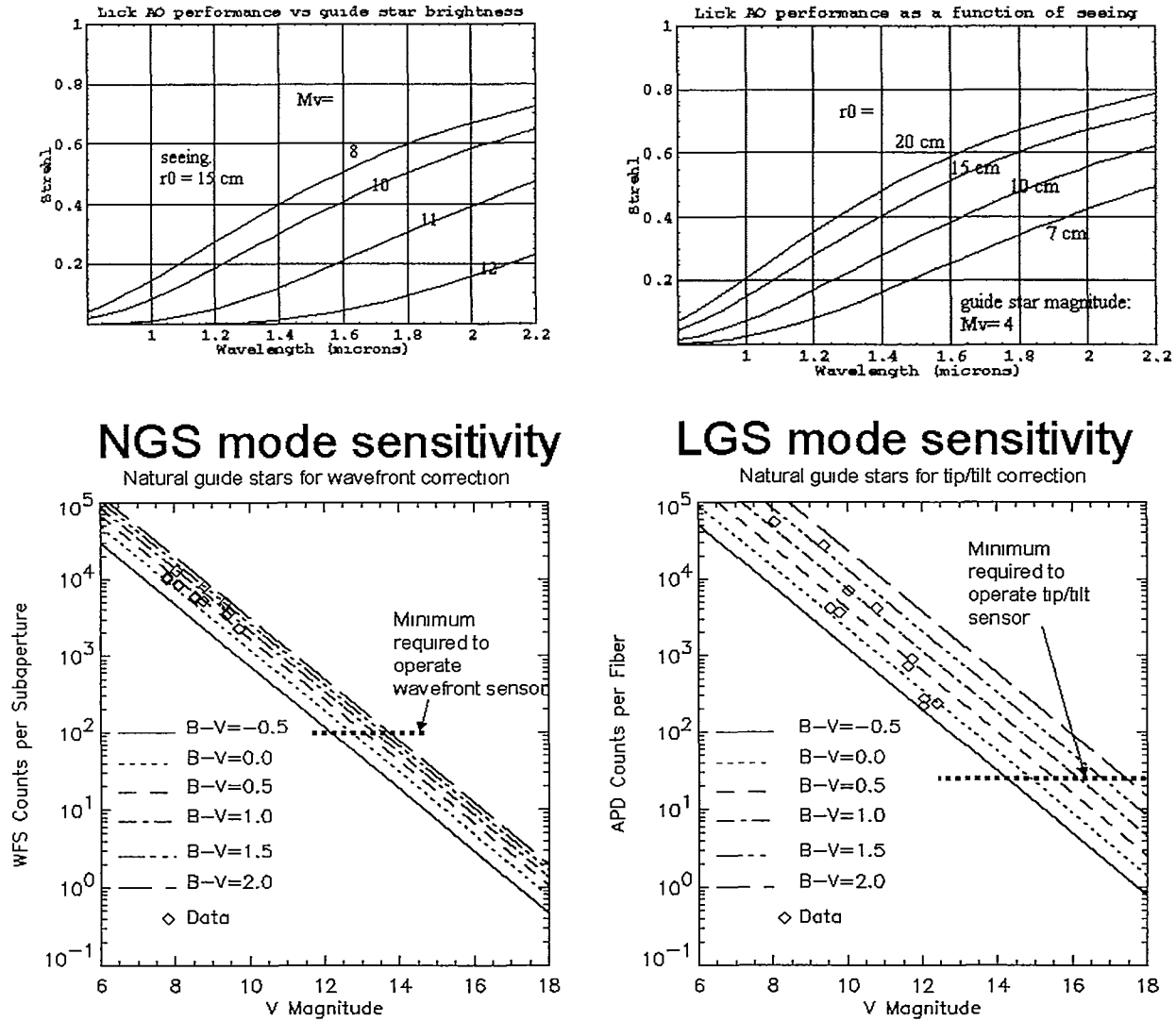


Figure 1: Performance of Lick Observatory AO system as a function of wavelength, seeing conditions, guide star brightness and guide star color.

4. Science

Applying AO to astronomy observations is still a relatively new field; techniques and applications are still being created as astronomers learn to apply their new tools. In short, though, the strengths of AO observing are as follows:

- Seeing previously undetectable details at or near the diffraction limit of the telescope--either qualitatively or quantitatively (via detailed knowledge of point-spread function)
- Detecting fainter objects, although this is difficult because of lower throughput (and hence higher thermal background)
- Increasing image contrast so as to allow detection of dim companions near bright objects
- Precision astrometry

Consistent with these strengths, the LLNL science that has been done is as follows, as reported in reference 15:

Formation of star systems: Researchers studied the formation rate of binary stars in the Pleiades and Hyades clusters and other star-forming regions of our galaxy. There is some evidence that the percentage of young stars in binary systems is higher than the percentage of mature stars in binary systems. This would imply that forming star systems are dynamically unstable and eventually kick out their orbiting companions. One young star system, a star cluster shown in Figure 1, has as many as 5 co-orbiting stars. This image demonstrates the resolving power of adaptive optics. Previous to these observations, ground-based observations resolved only two stars in the cluster.

Brown dwarfs: Scientists have been searching for low mass companion stars called brown dwarves. These are stars just above the mass limit to initiate nuclear fusion and are quite difficult to observe because of their low luminosity. They are scientifically interesting because they may be an important component of the mass of galaxies and their population densities can lead to a better understanding of the formation and evolution of galaxies. The AO system's resolving power acts to concentrate the dim star's light spatially, which helps to overcome background noise thus extending the lower limit of detectable luminosity.

Formation and detection of planetary systems: Astronomers have also been observing dim stellar companions to stars which are known from previous observations to have planets. There is a question of whether it is common for dynamically stable planetary systems to form around binary stars, or if planets are to be found only around single stars. This has profound implications on the statistics of planetary systems, since most stars are doubles. A spin-off technological benefit of this work is in the development of techniques that will be used eventually for detecting the planets themselves against the glare of their parent star. Detecting planets will require much larger telescopes and AO systems, however the development of the internal calibration technology and understanding of the point spread functions of adaptive optics, driven by the need to observe faint objects next to bright ones, are crucial to future success in this area.

Atmospheric chemistry of planets: Astronomers have been studying the atmospheric chemistry of Neptune. The AO system can resolve the dark regions of the atmosphere separate from the bright high-altitude clouds, allowing narrow band filters to probe to particular altitudes of the atmosphere in the unclouded regions (Figure 2). Understanding the optical depth profiles, and altitudes of various haze layers, allows us to gain better understanding of the energy balance between solar flux and internal heat sources on Neptune.

Extragalactic astronomy: Extragalactic astronomy is perhaps the most challenging of adaptive optics observations because these objects, galaxies and quasars, are not themselves bright enough to serve as natural guide stars. Recently, the approach has been to select extragalactic targets that are fortuitously near (as they appear to us) bright stars in our own galaxy. One galaxy type that has been observed is the radio galaxy, which emits brightly in the radio wavelengths because the host galaxies have an energetic core. AO infrared observations at high resolution allow the host galaxy to be identified and aligned to the radio observations. Some galaxies have quasars at their nucleus. A quasar is a very bright object associated only with very high red shift (young with respect to the age of the universe) galaxies. The AO system helps resolve the structure of the host galaxy giving insight into galaxy formation physics in the early universe.

5. Education

One of the benefits of the Lick Observatory Adaptive Optics System is that it has provided a training ground for current and future astronomers and adaptive optics scientists. Many of these individuals are channeled through the University of California and the National Science Foundation-funded Center for Adaptive Optics (CfAO), of which LLNL is a member; this nation-wide consortium of university, industry, and national laboratories is based at UC Santa Cruz. Since the Shane telescope is not one of the largest telescopes, its demand is lower than that of the 8-10m class telescopes. However, the adaptive optics system is comparable to that found on larger telescopes and allows students to learn adaptive optics observing techniques. In addition, the ease of access of the telescope to the constituencies of the University of California and California Institute of Technology (compared to the large telescopes on Hawaii) allows exposure to this relatively new method of observational astronomy.

KECK ADAPTIVE OPTICS

The Keck AO system is a result of a cooperative project with the Keck Observatory and UC/LLNL, and was aided by the insight gained on the Lick AO system. The following is a timeline of the Keck AO system development:

1994: System design of Keck AO system¹⁶,
1996: Design of wavefront control system¹⁷
1999: Delivery of wavefront control system
1999: First scientific images from Keck AO system¹⁸
2000: Delivery of dye laser to Hawaii to begin integration
2002: Delivery of dye laser to the Keck telescope
2002: First sodium laser guide star light¹⁹

In 1994, LLNL's knowledge of AO was incorporated in the design and build of the Keck Adaptive Optics system. The design tradeoffs and theoretical understanding were captured in Keck Report #208, the "Blue Book", which provided a conceptual design for the Keck AO system²⁰. Several contributors to the Blue Book were also instrumental to the building of the Lick AO system. In deliverables, LLNL contributed two important components of the Keck AO system: the dye laser for the sodium laser guide star, and the real-time controller for the AO system. In addition, LLNL provided key integration assistance during 1999-2001, resulting in stunning science images such as the Claire Max's images of storms on Neptune²¹ and Andrea Ghez's images of the galactic center²², shown in figures 2 and 3.

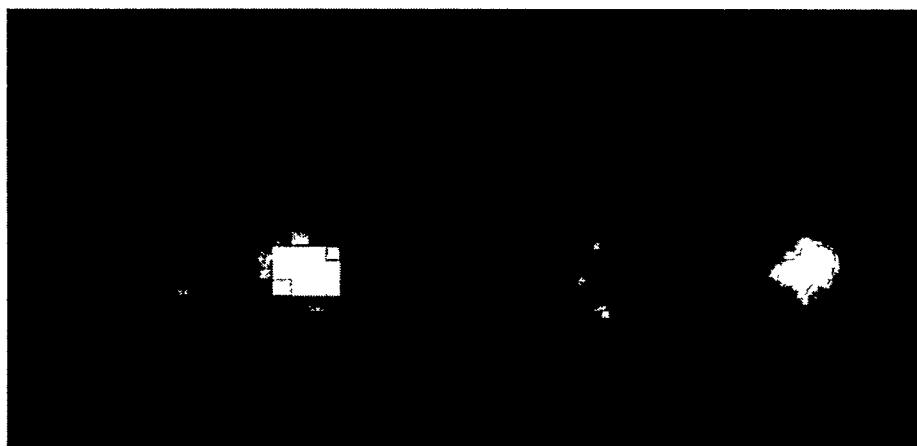


Figure 2: Images of Neptune with the Keck AO system, open loop (left) and closed-loop (right).

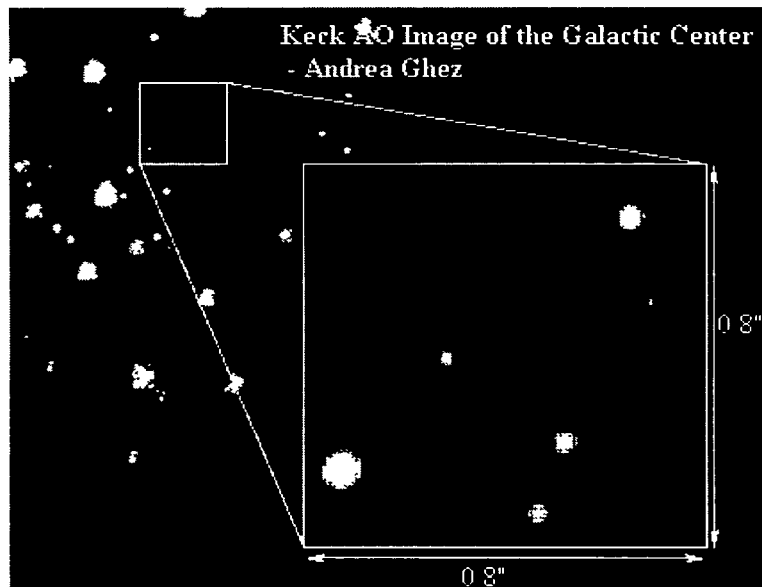


Figure 3: Keck AO image of Galactic Center. Approximate blur size without AO is 0.4'' (half the size of the larger box)

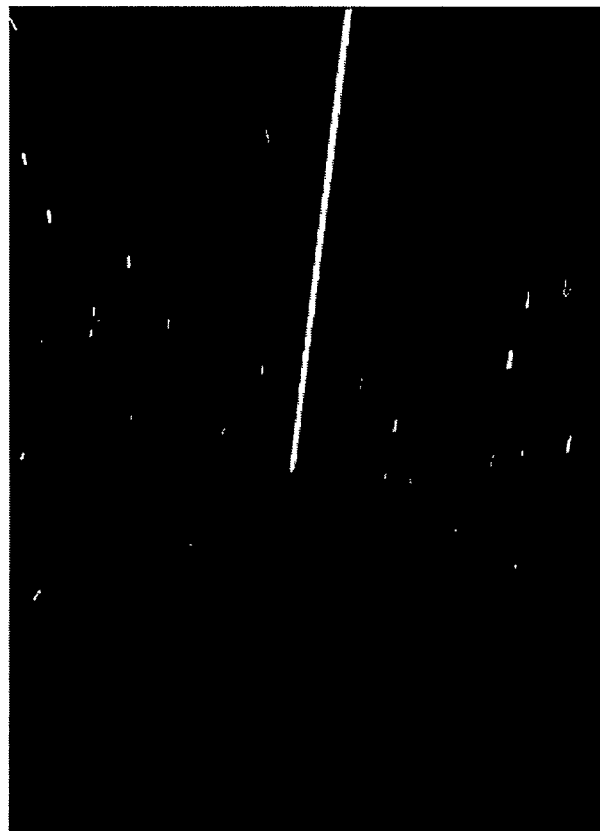


Figure 4: The sodium laser guide star at Keck Observatory (credit: Adam Contos, Keck Observatory)²³

Laser: In 2000, LLNL engineers and technicians completed delivery the 20 watt dye laser to Keck Observatory. This project included the facilitization of the laser to the mountain operating conditions. In 2002, the laser achieved “first light”²³

Today, LLNL staff continue to work on performance characterization and optimization of the Keck AO system. A two-year CfAO project led by LLNL astronomer Bruce Macintosh and LLNL scientist Marcos Van Dam aims to push the Keck AO system to its theoretical limits.

ADAPTIVE OPTICS ON EXTREMELY LARGE TELESCOPES

As important as adaptive optics has been in the past, it is becoming even more important in the next generation of astronomical telescopes: the Extremely Large Telescopes (ELT’s) in the range of 20-100m diameters. Of course, such large telescopes themselves present huge engineering challenges, but their AO systems are no less demanding.

UC and California Institute of Technology are partnering in the development of a proposal for a 30 meter diameter telescope. The conceptual design and the current understanding of the relevant design issues are encapsulated in the “Green Book.”²⁴

There are several outstanding issues in the development of the CELT AO system; LLNL, through its collaboration with the Center for Adaptive Optics (based at UC Santa Cruz), is participating:

Laboratory simulation: LLNL staff are aiding in the development of a Moore Foundation-funded Laboratory for Adaptive Optics, which will allow laboratory-scale implementations and testing of multi-conjugate adaptive optics (MCAO) and Extreme Adaptive Optics (EAO) techniques with ELT’s. Currently, these techniques have been computer-simulated and not yet reduced to practice. This laboratory is scheduled to be occupied in mid-2003.

Optics: The extremely long focal length of the CELT (450m), and the limitations of practical deformable optic sizes pose significant issues on the design of the AO relay near and beyond the cassegrain focus of the telescope.

Deformable optics development: Current costs of \$1000 per actuator in a deformable mirror would result in a several million dollar costs for the typical 5000-10000 element DM required by the ELT AO system. At first glance, the advent of micro electro-mechanical mirrors (MEMS) seems a good path to high actuator count DM’s; however, the optical design requirements temper one’s enthusiasm. Practical optical relays often require fields less than ~1-2 degrees for low-aberration performance; this sets a lower bound to the magnification of the AO relays, and thus sets a lower bound for the pupil size (\approx DM size). For a telescope of diameter 30m and FOV of 2 arcmin, the magnitude needs to be no more than about 60-120x, yielding pupil/DM sizes on the order of 250-500mm. Practical folding considerations increase the minimum DM size to approximately 350mm. Considering that the current maximum size of MEMS is about 10mm, a factor of 35 increase in size (or factor of 35 decrease in field) is required. Several DM development programs, funded by the Center for Adaptive Optics, are working on this issue.

Control algorithms: The demands of MCAO amount to the solving of a real-time highly “cross-coupled” tomography problem. This requires an efficient and accurate algorithm to allow convergence of the control-loop within the limited time constraints. The collaboration includes participants from many institutions in CfAO.

Reconstruction algorithms: New fast Fourier transform (FFT) – based reconstruction and centroiding techniques developed at LLNL offer the possibility of more efficient computations.

LGS development: Development of solid-state sodium guide star lasers will be a key issue. These lasers must be reliable, easy-to-maintain, easy-to-use, and easily scalable in power. LLNL engineer Dee Pennington is developing a new fiber laser technology that may solve many important operational issues.

EXTREME ADAPTIVE OPTICS

A number of researchers have found planets around other stars. Scientists infer the presence of these planets by radial-velocity spectroscopy, i.e., observing the small red- and blue-shifts that occur in the star's spectrum as the planet revolves around the star and tugs on it in varying directions. This method has found over 100 extrasolar planets, but only Jupiter-sized ones in earth-like orbits. Large-orbit planets are difficult to detect by this method, due to the long observation time required for larger orbits; small planets are difficult to detect due to the small radial velocities from smaller earth-like planets.

Extreme AO (ExAO) attempts to learn more about these planets and their formation history by *directly imaging* them. Direct imaging allows spectroscopic analysis of the planets, giving immediate insight into their formation histories. Extreme AO also allows detection of Jupiter-like planets in the large orbits beyond the "ice line" (inside which frozen water does not exist on planets) where giant planets are expected to form.

Currently, there is an effort within LLNL and CfAO to build an ExAO system for the Keck telescope. A simulation of expected results has been performed and the design has been started²⁵. This is a challenging project, requiring Strehl ratios >0.9 and coronagraphic attenuation of the parent star to achieve imaging of scenes with contrast ratios of 10^6 .

CONCLUSION

LLNL continues to play a major role in the development and use of adaptive optics systems for astronomy. LLNL has contributed and continues to contribute to workhorse AO systems such as the Lick AO system, leading edge systems such as the Keck AO system, and the future AO systems on large and extremely large telescopes.

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